High Current Linear Induction Accelerator for Electrons*

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A 150-A, 4-MeV electron accelerator has been designed and constructed for use in the "Astron" experiment. Design requirements include a beam quality less than 10^{-2} rad·cm and an energy spread of ±0.5%; the pulse length is 0.25 μsec and the repetition rate is variable to a maximum of 60/sec. The accelerating principle used is magnetic induction. Design features and the results of preliminary operation are discussed.

I. INTRODUCTION

THE key feature of the Astron concept[1,2] for containment and heating of the plasma is a cylindrical layer of relativistic electrons. A high intensity beam of electrons is injected in a cylindrical evacuated tank where an axially symmetric field is established by an external solenoidal coil. The injected electrons are trapped between two regions of enhanced field, oscillating back and forth along the evacuated tank. The electrons are injected in a field constant in time. In order to trap the injected electrons irreversibly, it is necessary to absorb part of their energy as they move from the injection to the trapping region. This is accomplished by forcing a bunch of injected electrons to pass through a region filled with resistor rings located concentrically with respect to the electron bunch. Eddy currents generated in the resistors absorb part of the electron energy, thus securing their trapping in the mirror field. In order to absorb a substantial portion of the electron energy, it is required that the beam current be as high as 100 A. It is expected that an adequate number of electrons will be trapped so that the combined vacuum field and the electron layer field will form a pattern of closed magnetic lines wherein plasma can be trapped. Thereafter the plasma can be heated by Coulomb collisions with the relativistic electrons. The parameters given in Table I were selected for the Astron accelerator which is now in operation.

Several types of accelerators were examined to determine their suitability for this application. First it was decided that some form of linear accelerator was more appropriate than a machine using a circular guide field. Among the familiar types of linear accelerators is the traveling-wave type,[3] consisting of an iris-loaded waveguide operating at microwave frequencies. This was rejected as a solution on two counts: one was the power level required during the beam pulse; the other, perhaps fatally serious, was the detuning effect of such large currents in this type of accelerator.[4] Another familiar type of radio-frequency linear accelerator is the standing-wave type, more usually used for ions.[5] Recently a machine such as this has been constructed for acceleration of high currents of electrons.[6] Because of our requirements for energy homogeneity and beam quality, preliminary designs did not seem attractive.

The principle of magnetic induction when applied to a linear accelerator seemed to offer the most attractive solution to meet the requirements stated in Table I.

TABLE I. Parameters of Astron electron accelerator.

Beam energy	4–5 MeV ±0.5%
Beam current	150 A
Pulse length	0.25 μsec
Repetition rate	0–60/sec
Beam quality	$<10^{-2}$ rad·cm

II. MAGNETIC INDUCTION PRINCIPLE

The principle of magnetic induction has been applied to the acceleration of electrons in the familiar betatron[7] and in the initial acceleration in the electron synchrotron. The geometry shown diagrammatically in Fig. 1 was utilized to apply this principle to a linear accelerator. A toroidal ring

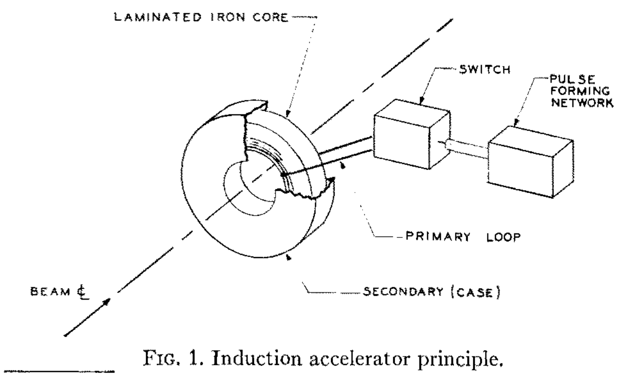

FIG. 1. Induction accelerator principle.

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[1] N. C. Christofilos, Proc. U. N. Intern. Conf. Peaceful Uses At. Energy 2nd, Geneva **32**, 279 (1958).
[2] N. Christofilos, "Astron Electron Injection," Lawrence Radiation Laboratory (Livermore) Rept. UCRL-5617-T (22 June 1959).
[3] M. Chodorov, E. L. Ginzton, W. W. Hansen, R. L. Kyhl, R. B. Neal, and W. K. H. Panofsky, Rev. Sci. Instr. **26**, 134 (1955).
[4] N. A. Khizhnyak, V. T. Tolok, V. V. Chechkin, and N. I. Nazarov, J. Nucl. Energy, Pt C **4**, 129 (1962).
[5] L. Smith in *Encyclopedia of Physics, Nuclear Instrumentation* I, edited by S. Flugge (Springer-Verlag, Berlin, 1959), Vol. XLIV, p. 341.
[6] D. Venable, Rev. Sci. Instr. **33**, 456 (1962).
[7] D. W. Kerst, Phys. Rev. **60**, 47 (1941).

of magnetic material surrounds an accelerating column, and the change in flux in this magnetic core induces an axial electric field.

The volt-seconds available to this system for a given magnetic material depends upon the cross-sectional area of the toroidal ring as indicated by the expression

$$\oint \mathbf{E}\cdot d\mathbf{l} = -\frac{1}{c}\int_s \frac{d\mathbf{B}}{dt}\cdot d\mathbf{s}, \quad (1)$$

where the particle to be accelerated performs the integration on the left side and the surface integral is taken over the cross section of the ferromagnetic material.

Hence, for a given weight of material, the beam pulse length influences the energy gain. Further, since it is the cross section that determines the energy available, a premium is put on minimizing the diameter for two reasons. The first is to minimize the total weight of magnetic material and hence its cost, and the second is to minimize the power for magnetization which is also proportional to volume.

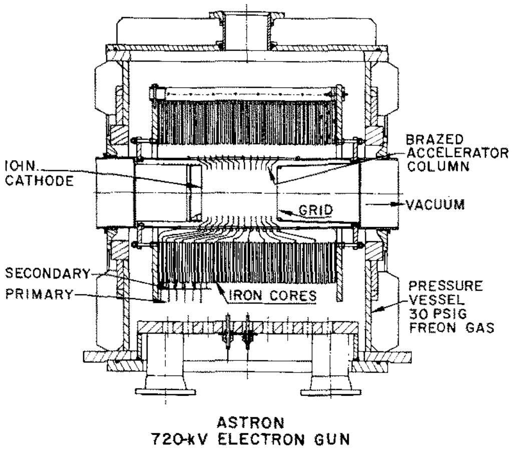


FIG. 2. Gun section.

The requirement for energy uniformity during the beam pulse makes it necessary to make some provision in the pulsing system to maintain a constant dB/dt during the useful part of the pulse. This can be done by providing a current ramp in the primary pulse.

The choice of magnetic material was made by testing various samples to determine all of the properties which are important in this application. The material selected was 0.001-in.-thick Ni-Fe tape wound into cores. The saturation flux of this material is 8000 G, which permits a total flux change of 16 000 G.

III. THE ELECTRON GUN

The electron gun designed for this accelerator consists of a cathode and an accelerating system utilizing the induction principle. It is a requirement to minimize the transverse acceleration while the beam is at low energy. For this reason a 10-in.-diam cathode was used; this results in an initial current density of the order of 1 A/cm^2.

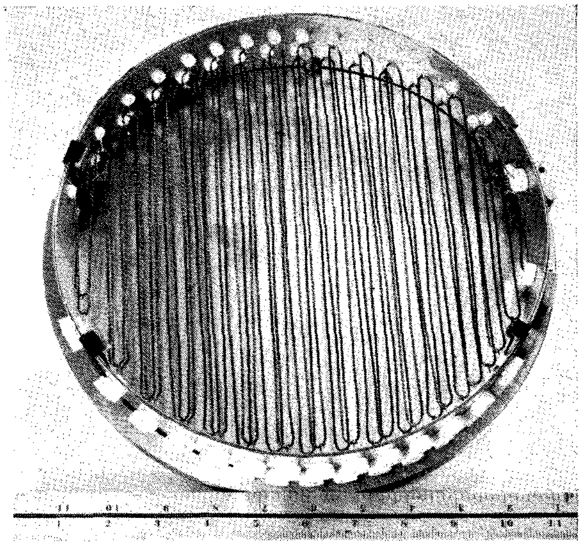


FIG. 3. 10-in. cathode heater assembly.

The required gradient is given by the Poisson equation for relativistic electrons in polar coordinates. A cross section of the gun assembly is shown in Fig. 2. The required field gradient is obtained by adjustment of electrode spacing and the number of cores between successive gaps. Each core contributes an average of 14 keV to the beam.

The entire gun assembly is installed in a pressure tank which is pressurized to two atmospheres of a mixture of Freon 12 and dry nitrogen. A blower circulates this gas through a heat exchanger to remove the heat generated in the system.

The vacuum tube and the electrodes are constructed of 14-in. metal-ceramic seals in two parts which are welded together in the center. The cathode is a conventional oxide cathode on a sintered carbonyl nickel base. It is heated by radiation on the heater assembly shown in Fig. 3.

Each core is threaded by three primary straps symmetrically placed and one monitor strap. Considerable attention was given during the development to insulating materials used in the assembly. Even though the spacings and voltages involved are conservatively chosen, the short pulses employed cause insulation failure and short lifetimes. Considerable testing was required before materials could be chosen whose service lifetime was judged satisfactory.

IV. THE ACCELERATOR

The accelerator consists of the electron gun and six modular units of 48 cores each (Fig. 4). The accelerator modules are constructed around a metal-ceramic vacuum tube 6 in. in diameter. This tube is made up of eight elec-

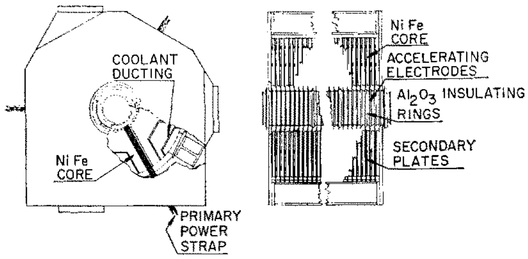


FIG. 4. Induction accelerator unit.

trode modules welded together into a continuous column. The core, primary straps, and insulation are similar to those described previously for the gun; however, the cooling is by forced circulation of room air by means of blowers.

The electric field across the accelerating gaps at radius r_0 can be expanded in a Fourier series,

$$E_Z = E_0 \sum_n a_n \cos(nkZ), \tag{2}$$

where $k = 2\pi/s$ and s is the distance between accelerating gaps. The free space wavelength corresponding to the pulse length is over a thousand times the diameter of the accelerating column. Hence a solution of the Laplace equation is a good approximation of the field distribution. Therefore, the electric field within the accelerating column is given by

$$E_Z = E_0\left[1 + \sum_n a_n \beta_n I_0(nkr) \cos(nkZ)\right], \tag{3}$$

where $\beta_n = [I_0(nkr_0)]^{-1}$.

All the higher harmonics of this solution are undesirable, and they must be suppressed to a small value. By selecting the radius r_0 of the electrode rings about twice the beam radius, and the accelerating gap about three to four times smaller than the radius r_0, the higher harmonics are suppressed to about 1% of the accelerating field.

One of the requirements of the accelerator is that the final beam radius be about 1 cm, therefore additional focusing is required. As a high current electron beam is accelerated to energies where relativistic effects are important, the magnetic forces associated with the beam's self-magnetic field become very nearly equal to the electrostatic forces due to the charged particles in the beam. The net force in the absence of positive charge is always repulsive, but it is diminished by the factor γ^{-2}, where γ is the ratio of the electron's relativistic mass to its rest mass.

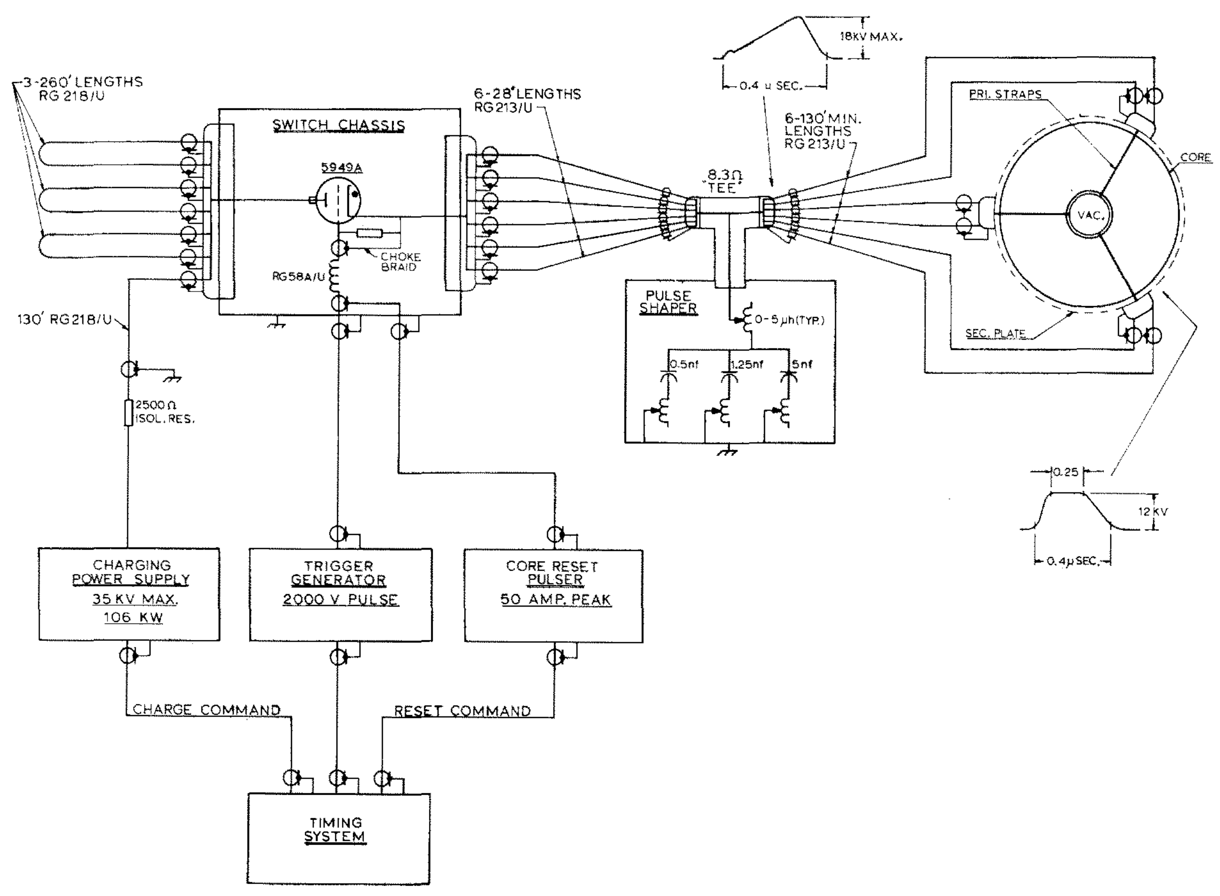


FIG. 5. Simplified schematic of modulator system.

Therefore, as the beam is accelerated it is periodically focused with solenoidal lenses until the final beam radius of about 1 cm is achieved.

V. THE PULSER SYSTEM

The electronic system for this type of accelerator is really what finally determines the performance and reliability of the machine. The basic requirements are to induce the maximum practical flux change in each core, and as far as possible, maintain a constant flux change and consequently a constant electric field during the useful part of the pulse. Figure 5 is a block diagram of the components of the system adapted for use on this machine with the general specifications and waveforms when appropriate. The development of this equipment is discussed in a previous publication[8]; however, the following is a brief description of the function of the system.

Table II lists the chief performance requirements of the pulser system.

TABLE II. Typical core pulsing requirements.

Item	Gun core	Accelerator core
Peak primary voltage[a] (V)	16 000	12 000
Peak input current[a] (A)	4500	1800
Peak power input[a] (MW)	70	21.6
Maximum input impedance (Ω)	12.5	17.5
Minimum input impedance (Ω)	2.9	6.0
Primary voltage risetime (nsec)	40	40
Secondary voltage risetime (nsec)	40	40
Primary voltage fall time (nsec)	60	60
Secondary voltage fall time (nsec)	60	60
Pulse duration over ±0.50% portion (μsec)	0.25	0.25

[a] Measured at the end of the 0.25-μsec flat region of pulse.

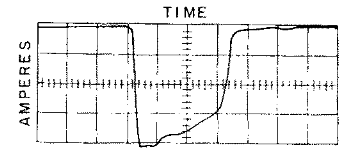
Resonant charging of the energy storage cables was chosen to minimize the time of maximum voltage stress. The output cables have to be long enough so that the reflection due to mismatch at the load would not arrive during the pulse; hence the minimum length was 130 ft.

Several milliseconds before the pulse-forming networks are charged, each core is taken into saturation in the negative direction by a reset pulse of 50 A which persists for 200 μsec. This ensures that all the volt-seconds available in each core can be used efficiently when the thyratron switch chassis are fired.

Figure 5 shows a schematic of the pulse shaper chassis. These are devices in parallel with the cores that store energy during the pulse and deliver the stored energy late in the pulse. This produces a current ramp which can be adjusted to give the required ±0.5% voltage pulse from each core.

[8] V. L. Smith, IRE Trans. Nucl. Sci. **NS-9**, 57 (April 1962).

FIG. 6. Beam current pulse monitored by a Faraday cup (40 A/cm, 0.1 μsec/cm).



VI. PRELIMINARY ACCELERATOR OPERATION

Most of the operation has been at 5 or 10 pps (pulses per second). The accelerator has produced average currents of 140 A for pulse durations of 0.3 μsec. The peak currents as shown in Fig. 6 are about 160 A; however, the current pulse amplitude is not constant in time and the average is 140 A. The current pulses are monitored in a deep Faraday cup which has a 50-G transverse magnetic field at the back of the cup. This magnetic field is sufficient to trap all low energy secondary electrons, and the small solid angle is relied on to reduce the effect of escaping back-scattered primary electrons. The current is monitored by measuring the voltage produced across a very low inductance 0.5-Ω resistor attached to the Faraday cup.

The beam energy has been measured to be 4.0±0.1 MeV. The energy was determined in two ways. One method is a calorimetric measurement using a water-cooled Faraday cup. Another method involves adding up all the voltage pulses from the core monitor straps. Each core has a precision voltage divider attached to its monitor strap. These voltage dividers were calibrated by turning off accelerator units and individual cores until the threshold for the photodisintegration of deuterium was established.

The initial operation of the full accelerator commenced in mid-February 1963. The accelerator consists of the electron gun and six accelerator units. This requires the simultaneous operation of 333 cores and 423 switch chassis. Each gun core requires three switch chassis. Twelve hundred hours of operating time has established a mean time to failure of about 4 h. It is expected that the mean time to failure can be improved. However, the accelerator

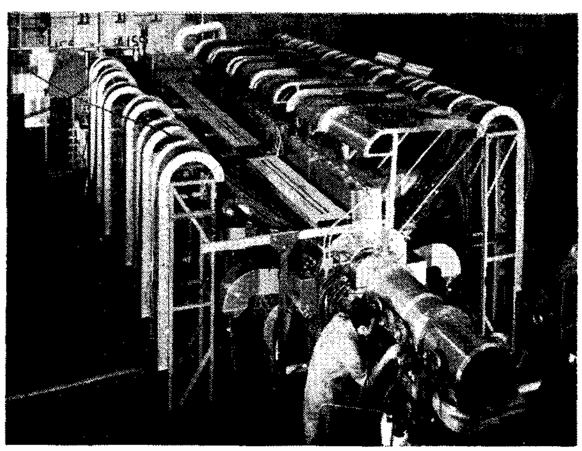


FIG. 7. Overhead view of the Astron accelerator as it appeared when first put into operation.

consists of many modular units and the failure of a module only removes one core from operation. This results in less than 1% beam energy loss, therefore a failure during operation need not terminate an experiment.

Figure 7 shows an overhead view of the Astron accelerator as it appeared during initial operation.

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Prototype of a Portable Microcalorimeter for Measurement of Absorbed Dose

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A prototype of a compact, portable microcalorimeter has been built which measures ionizing radiation dose rates as low as 3 rads/min measured in aluminum. The absorber and temperature sensing system are conventional but the temperature-controlled bath which usually surrounds a vacuum chamber in such microcalorimeters has been replaced by an aluminum isothermal shield bolted to the bottom surface of a copper reservoir containing liquid nitrogen. Both the shield and the reservoir are contained in a vacuum chamber. Calibration of the absorber is accomplished by observing the response of an imbedded thermistor when the calorimeter is placed in a gamma-ray field of known exposure level provided by a 200-Ci ^{60}Co source.

INTRODUCTION

It is often desirable to describe quantitatively the effects of ionizing radiation upon matter in terms of the actual energy absorbed by the matter during the irradiation. This amount of absorbed energy is called the absorbed dose and is expressed in units of rads, where the rad is defined as 100 ergs of absorbed energy per gram of absorbing material. In most materials the absorbed energy is entirely converted to heat energy, and thus the measurement of the temperature rise of the irradiated material provides a fundamental and direct method of determining absorbed dose. The advantages of the calorimetric determination of absorbed dose have been demonstrated in earlier investigations and have led to the recommendation that it be used for primary standardization of absorbed dose for photon energies above 1.0 MeV.[1,2]

During the past year a microcalorimeter has been used at this Laboratory for absorbed-dose measurements with various types of ionizing radiation (gamma rays, fast neutrons, and 900-MeV alpha particles). The microcalorimeter used is similar to that used by Bernier *et al.*[1] and Reid and Johns.[2] As the result of experience with this calorimeter, it has become apparent that there is a need for a calorimetric method of dosimetry which provides the calorimeter's freedom from energy and dose-rate dependence in an instrument having portability without sacrificing sensitivity. Petree[3] and Genna[4] have described calorimeters in which portability has been attained by eliminating the controlled temperature bath which usually surrounds the absorber. In both these calorimeters heat exchange with the surrounding is minimized by means of a jacket which is held at the temperature of the absorber by electrical heating. However, the sensitivity of the Petree apparatus apparently sets a minimum dose-rate limit of approximately 50 rads/min, and the Genna calorimeter, although of greater sensitivity, has been used only in environments having a well-controlled temperature.[5]

In the following sections a calorimeter will be described in which portability has been attained by replacing the bath by a metal shield held at a constant temperature by contact with a small liquid-nitrogen reservoir. Details of the construction, operation, and calibration of a prototype making use of this approach will be presented.

CALORIMETER DESIGN

The requirements which have been established for the design of a portable calorimeter follow: (1) Portability to permit ease of movement from one laboratory to another; (2) compactness to permit installation in small spaces and in close proximity to radiation sources; (3) minimum time requirements for setting up and reaching thermal equilibrium; (4) simplicity of construction and instrumentation;

[1] J. P. Bernier, L. D. Skarsgard, D. V. Cormack, and H. E. Johns, Radiation Res. **5**, 613 (1956).
[2] W. B. Reid and H. E. Johns, Radiation Res. **14**, 1 (1961).
[3] B. Petree and G. Ward, Natl. Bur. Stds. (U. S.) Tech. Note 163, (1962).
[4] S. Genna, R. G. Jaeger, J. Nagl, and A. Sanielevici (unpublished).
[5] J. Nagl (private communication).